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PART II

PRINCIPAL MINERAL DEPOSITS

IRON ORES

On the basis of their physical properties, which to some degree separates them also according to chemical composition, the iron ores[1] of Minas Geraes may be classified as follows.

[1] H. K. Scott, "The Iron Ores of Brazil," *Jour. Iron and Steel Institute*, LXI, (1902), 248; O. A. Derby, "The Iron Ores of Brazil," *Iron Ore Resources of the World*, p. 313, Stockholm, 1910; C. K. Leith and E. C. Harder, "The Hematite Ores of Brazil and a Comparison with the Hematite Ores of Lake Superior," *Econ. Geol.*, VI, (1911) 670–86; E. C. Harder, "The 'Itabirite' Iron Ores of Brazil," *Econ. Geol.*, IX, (1914) 101–11; E. C. Harder, "The Iron Industry in Brazil," *Bull. Am. Inst. Mg. Engrs.*, October, 1914.

Original or Bedded Ores
- Hard massive ore
- Soft powdery ore
- Laminated or thin-bedded ore

Concentration Ores
- Canga
- Stream sand and gravel ores
- Rubble ore
- Enriched itabirite
- Leached carbonate

Of these the bedded ores, especially the hard massive ores, are by far the most important. Of the concentration ores the canga is the principal type.

Bedded ores.—Bedded iron ores are found in many places in central Minas Geraes, but the most important deposits occur in the region surrounding the headwaters of Rio Piracicaba, Rio Carmo, Rio das Velhas, Rio Santo Antonio, and Rio Paraopeba, together with their various branches and tributaries. This is the region in which the Itabira iron formation has survived the extensive denudation which has swept away the post-Archean formations from much of eastern Brazil, and where it still remains as a thick formation over considerable areas. The ore bodies occur at various points along the belts of iron formation already described, both in the Itabira iron formation proper, and in the iron-formation lenses in the Piracicaba schist. They are not irregularly scattered throughout the iron-formation areas, but are rather grouped in certain portions with barren areas between. Thus groups of iron-ore deposits occur north of Ouro Preto on the east slope of the Serra do Caraça;[1] on the Rio Piracicaba west and northwest of the town of Villa Rio Piracicaba; on the prominent peaks at Itabira de Matto Dentro; along the ridge running from Sabara northeastward to Caethé and southwestward beyond Bello Horizonte; at various points in the area west of Itabira do Campo, and in the region west of Burnier and north of Gongonhas do Campo. Smaller, less important groups occur elsewhere in the district.

The bedded ores occur as beds or lenses in the iron formation. Some are thin and continuous for long distances, while others are

[1] See map on p. 347, Part I of this article.

thick and of small diameter. Of the three classes of bedded ores, hard massive ore and the peculiar soft powdery ore are the most widespread, the latter probably being the more common of the two. Laminated ore is less widespread, but generally occurs in larger deposits.

The hard ore of central Minas is of several varieties, the most common of which is a slightly specular blue hematite resembling

FIG. 12.—The Peak of Cauê rising above the town of Itabira de Matto Dentro. A large body of hard ore.

some of the specular hematite ores on the Marquette range in Michigan. Such ores occur in many places in the district. Locally there are deposits consisting of coarsely specular hematite with scattered crystals of martite, and with these are frequently associated ores composed largely of coarse granular masses of martite, or magnetite not yet completely altered to hematite. Such phases are due probably to greater metamorphism and are most common in the eastern part of the district. In the central and western part of the district there occur a few deposits of a tough, fine-grained, almost amorphous hematite, or hematite intermixed with some limonite.

Some hard ore deposits, or parts of these deposits, are so massive that the bedding is barely distinguishable while other portions may be distinctly bedded. The material is generally well consolidated, and some phases, especially the amorphous variety, are of extraordinary hardness and toughness.

Of the different varieties of hard ore the finely specular type is the highest grade. It generally averages between 69 and 70 per cent in metallic iron and rarely has more than 0.025 per cent phosphorus and frequently runs as low as 0.003 per cent phosphorus. Other impurities are practically absent.

The soft, powdery ore deposits consist largely of unconsolidated material of great fineness, most of it so fine-grained that it will easily pass through a 100-mesh screen. Although fine, the material is almost entirely crystalline, quite different from the amorphous powder which occurs with much of the soft ore on the Mesabi Range in Minnesota. Some of the powdery ore is slightly consolidated when moist, but readily crumbles when dried. Most of it, however, is soft in the moist state like fine moist sand.

The powdery ore is dark blue in color like the hard ore and resembles it in composition, though in general perhaps of slightly lower grade as it is more frequently intermixed with a sprinkling of quartz sand. It averages between 67 and 69.5 per cent metallic iron and contains up to 0.05 per cent of phosphorus, though it may run as low as 0.004 per cent of phosphorus. When the amount of quartz sand increases in the soft ore the metallic iron content decreases until the arbitrary figure of 50 per cent metallic iron is reached, when the material is classified as itabirite. Some of the soft ores, just as in the case of some of the hard ores, are almost without evidence of bedding, while others are distinctly bedded and even finely laminated. Where quartz sand is intermixed with the soft ore the bedding is well marked.

Hard ore and soft ore are generally more or less associated with each other. In general it may be said that massive specular ore and soft, powdery ore are hard and soft phases of the same material (Fig. 13). A deposit composed principally of hard ore may have lenses of soft ore or irregular masses of soft ore scattered through it, or portions of it may be composed of a mixture of hard

ore fragments and soft ore, the latter acting as a matrix. On the other hand, deposits consisting largely of soft ore may have hard ore lenses interbedded with the soft ore.

The soft, powdery ore is known among the natives of the iron region as "jacutinga," and since this term has also crept into the literature its meaning should be clearly defined and its misuse avoided. The term "jacutinga" was applied by Hussak[1] to

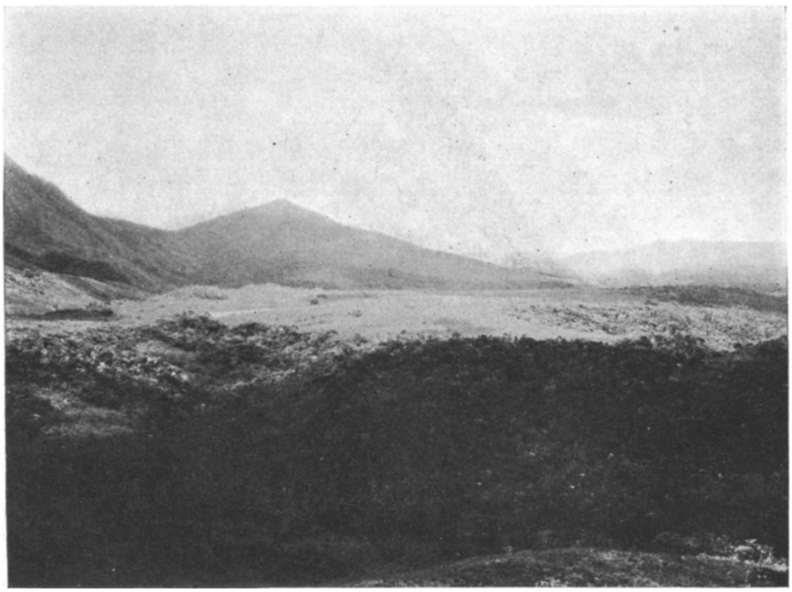

FIG. 13.—The Peak of São Luis near the village of Agua Quente. In front of the peak is a plain surfaced by canga. The steeply inclined beds of iron formation which appear in the peak continue under the canga covering of the plain. In the peak they consist partly of itabirite and partly of hard ore; under the plain the same beds consist of soft, powdery ore and soft itabirite. On the extreme left is the Caraça quartzite range.

certain gold-bearing portions of the iron formation. The jacutinga thus designated occurs in the form of shoots and irregular masses inclosed in itabirite from which it differs in a minor way only. It has a variable composition, and its principal characteristic is a fine

[1] E. Hussak, "O Palladio e a Platina no Brazil," *Annaes da Escola de Minas de Ouro Preto*, N. 8 (1906), p. 96, tr. by Miguel A. R. Lisboa, and Manoel A. R. Lisboa.

micaceous texture. It consists mainly of soft hematite in which quartz occurs in varying abundance together with talc, kaolin, mica, and earthy pyrolusite and frequently tourmaline. Presumably the term as used by Hussak includes those portions of the iron formation which have been affected by gold-bearing solutions, and it seems best to limit its use in the future to this phase and to avoid its use in the iron-ore terminology.

The bedded ores of the third class, the laminated, are distinct from those of the other classes and more closely resemble the itabirite in texture. These ores might be termed itabirite with little or no quartz sand. They occur in large lens-like deposits in the iron formation, as do the hard ores and soft ores, but the boundary between one of these lenses and the itabirite of the iron formation which incloses it is less well defined and more irregular. While the hard ore and soft ore deposits generally have a sharp contact with the inclosing itabirite, the laminated ore deposits generally have a zone of gradation with the itabirite and also have interbedded masses of itabirite within them. The separation of itabirite from laminated ore is frequently quite arbitrary, being controlled by the percentage of metallic iron.

Lenses of hard ore or soft powdery ore occur interbedded within laminated ore deposits in the same way that they occur in the itabirite portions of the iron formation. In such cases the contact with the hard ore is well defined, but that with the soft ore less so.

Laminated ore is a very thinly bedded, porous ore which is quite friable, breaking into thin plates along bedding planes, owing to the fact that the porosity is concentrated along these planes. The ore is red or blue hematite, much of it in the amorphous form, with a considerable percentage of limonite. The different varieties of laminated ore are generally found interbedded or interlaminated. Certain beds may be red, others blue, and still others yellow, the differences being the result of hydration and slight admixtures of clay and other impurities. Frequently siliceous beds of different thicknesses will be found interbedded with pure ore.

The laminated ore is not so high in grade as the hard ore and soft ore, for the metallic iron content of its richer portions varies

between 63 and 67 per cent, while the hydrated portions frequently contain as high as 0.3 per cent phosphorus and rarely less than 0.05 per cent phosphorus. It is mainly a non-Bessemer ore. With increasing quartz sand the content of metallic iron decreases until the material becomes itabirite. Non-hydrated, laminated ore resembles soft, powdery ore in composition.

The phosphorus content of the surface ores is always higher than that of the ore underground. Where surface ore contains 0.12 to 0.18 per cent phosphorus, underground ore may contain only 0.04 to 0.08 per cent. This is due to the concentration of phosphorus during the process of weathering. This same process also concentrates the iron in the uppermost foot or two, hardening it and decreasing the pore space.

The size of the different ore deposits varies from mere seams inclosed in itabirite to beds several kilometers in length and several hundred meters in thickness. The largest known deposits are of laminated ore, but there are also hard ore deposits of large size. The largest known laminated ore deposit in the district is that of Alegria, where continuous outcrops occur over a distance of more than 4 kilometers along the strike of the beds and for fully 1,700 meters across the beds. With an average dip of 35° the thickness would be at least 1,200 meters.[1] This great thickness, however, is not entirely of pure ore, but will possibly be found to include numerous minor beds of itabirite now concealed at the surface. The largest body of hard ore in the district, which, however, has a considerable admixture of soft ore and of hard ore fragments intermixed with soft ore, is that of Periquito near Itabira de Matto Dentro. It has a length of 1 kilometer and a maximum thickness at right angles to the beds of 250 meters. Other large deposits of hard ore are known in which the proportion of soft ore is very small. Such are the peak of Caué (Fig. 12), the deposits on Serra de Conceiçao and Serra do Esmeril near Itabira de Matto Dentro, Itabira Peak near Itabira do Campo, and Morro Agudo Peak near Villa Rio Piracicaba. Deposits consisting largely of pure soft powdery ore are as a rule much smaller than hard ore deposits but more numerous.

[1] See Fig. 4 on p. 354, Part I of this article.

Concentration ores.—Concentration ores occur in the neighborhood of other ore deposits or of iron-formation beds by the disintegration of which they are formed. They are in the form of surface deposits and do not go to a great depth. Of such deposits the canga ores are the most widespread, occurring as surface blankets of great horizontal extent over a large portion of the areas of iron formation, as well as over areas of other rocks bordering the iron-formation

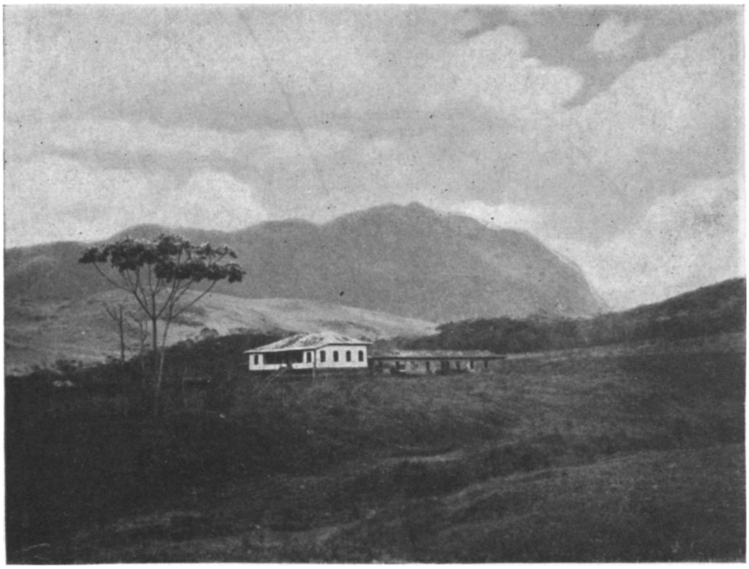

FIG. 14.—The Fazenda de Alegria. The prominent mountain is the Serra do Caraça. The lower range of hills in the middle distance are the hills of laminated iron ore. The ranch house is built upon canga-covered Piracicaba schist.

belts. They are composed of material resulting from the disintegration, not only of the iron ore portions of the iron formation, but from the itabirite phase as well.

Canga consists of different sized fragments of iron ore mixed in places with fragments of itabirite, the whole cemented together by iron oxide. The incorporated fragments vary in size from sand grains to bowlders weighing perhaps several tons. Some of them consist of pure massive ore, others of laminated ore or itabirite. The fragments have been mechanically concentrated and have

been cemented together by iron oxide deposited from solution, both fragments and cementing material being derived from the same source—the iron formation. The cementing material is largely hydrated hematite and limonite, red or yellow in color, giving different portions of canga deposits colors varying from light yellow to dark red. The fragments decrease in size and abundance as the distance from the source increases, so that in one place a canga deposit may consist largely of cemented fragments and elsewhere of finely textured chemically deposited iron oxide. The latter is most common over areas outside the iron formation or over soft portions of the iron-formation belts where erosion yields no coarse fragments. In the latter localities, however, much fine fragmental material is intermixed. In places at a distance from the iron-formation areas the canga is very low grade, containing much clay and quartz sand, the iron oxide present being principally limonitic cement.

The ordinary canga of which the great portion of the canga deposits are composed averages between 60 and 65 per cent metallic iron and up to 0.3 per cent phosphorus, rarely containing less than 0.1 per cent phosphorus. This concentration of phosphorus is due to the same cause as the concentration of the phosphorus in the surface laminated ore. The outlying portions of canga deposits at a distance from the iron-formation belt are so low in metallic iron that they do not constitute an iron ore.

A canga blanket may vary in thickness in different portions from a few centimeters to 20 meters or more. It is generally thickest on the lower slopes and at the base of iron-formation ridges, where the conditions for accumulation are best, and decreases in thickness both up the slope and toward the valley. A single continuous blanket of canga may cover several square kilometers.

Stream deposits of iron oxide in the form of sand, pebbles, and larger fragments occur in greater or less purity along most of the streams rising in or flowing through areas of iron formation. The material is distributed over the width of the valley floors and in places occurs in terraces several meters above the present valley bottom. The stream deposits do not constitute a very high-grade ore, always being mixed with more or less quartz sand and other

foreign material. They are of little or no importance as an ore reserve.

Rubble ore deposits occur on the hill slopes below outcrops of hard ore. They are simply talus accumulations consisting of high-grade iron ore, and frequently are large enough to be of some importance for mining purposes. The fragments composing them may vary in size from pebbles to fragments of several tons. In

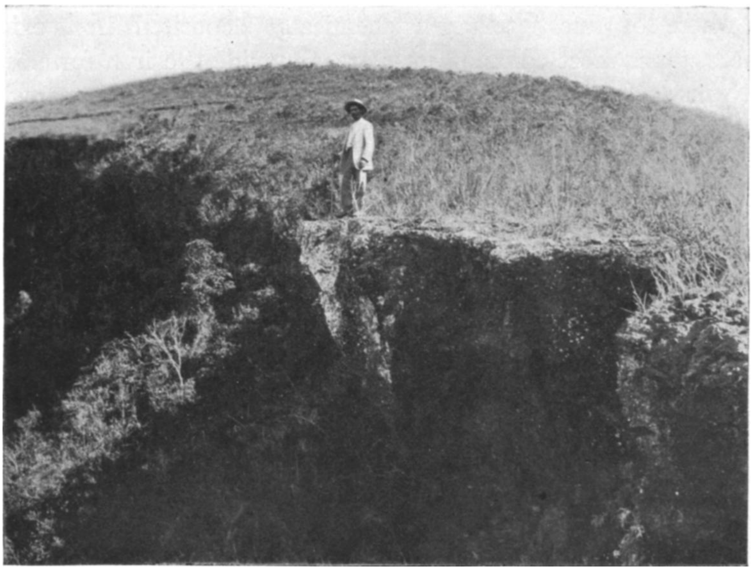

FIG. 15.—A cliff of canga on the side of the "Grotto" in Esmeril near Itabira de Matto Dentro. The canga blanket here reaches a thickness of about 15 meters.

many places, however, one finds rubble ore deposits with fragments remarkably uniform in size. Rubble ores have practically the same composition as the hard ore deposits with which they are associated.

Small deposits of enriched itabirite occur locally, but are of little importance. They might be termed canga deposits formed *in situ*, as they occur at the surface in itabirite areas where the leaching of silica has been sufficient to leave the residual material concentrated as iron ore. Frequently the iron oxide itself has been dissolved and redeposited in the form of limonite in pores and along

cracks as veins and stringers. In some places manganese oxide (psilomelane) is associated with this redeposited material.

The lenses and beds of carbonate rocks in the lower part of the Piracicaba formation in places contain a noticeable percentage of iron and manganese carbonates. On decomposition these form impure residual deposits of iron and manganese oxides.

Origin of the bedded ores.—From the structure and shape of the bedded ore deposits and their relation to the inclosing rocks it is necessary to conclude that they are original sedimentary deposits, laid down in a measure similar to limestone beds. They are simply a part of the iron-formation beds, similar in origin to the itabirite with which they are associated, except that they contain a smaller proportion of mechanical sediments, such as quartz sand. It is, therefore, best to explain the origin of the iron formation as a whole and note the differences in origin between the itabirite portions and the iron ore portions.

As has been stated, the iron formation is, in the main, an iron-oxide-bearing sandstone or quartzite. It varies in different portions from a rock consisting largely of quartz sand to one consisting of pure iron oxide. The siliceous portions of the iron formation are called itabirite, just as the siliceous portions of the Lake Superior iron formation are called ferruginous chert, jaspilite, or taconite. The portions rich in iron oxide are termed massive ore, powdery ore, or laminated ore, according to their texture. The line between the itabirite and the iron ore, especially the laminated ore, is arbitrary, depending on the percentage of metallic iron present. At the present state of the iron industry, iron formation with 50 per cent or more of metallic iron may be termed iron ore and iron formation containing below 50 per cent metallic iron itabirite. In the Brazilian iron formation there are no equivalents of the cherty iron carbonate and the greenalite rock of the Lake Superior district which in that region represent the original rock from which the iron ore, ferruginous chert, and associated rocks have been formed by weathering. In the Brazilian iron fields there has been no such alteration, the itabirite and iron ore being the original rocks.[1]

[1] C. K. Leith, and E. C. Harder, "The Hematite Ores of Brazil and a Comparison with the Hematite Ores of Lake Superior," *Econ. Geol.*, VI (1911) 670–86; E. C. Harder, "The 'Itabirite' Iron Ores of Brazil," *Econ. Geol.*, IX (1914), 101–11.

The iron formation has all the characteristics of a sedimentary deposit, although, just as in the rest of the Minas series, fossils have not been recognized in it. Portions are very massive and exhibit little or no evidence of bedding, as is frequently seen in massive quartzites, while other portions are thin-bedded or finely laminated, as shales and fine-grained sandstones. In the thinner-bedded portion the bedding or lamination planes are for the most

FIG. 16.—The Fazenda de Alegria. The highest peaks behind are of Caraça quartzite. The strong range of hills in front are of iron formation. To the left of the deep notch they are chiefly of itabirite; to the right of it dominantly of laminated iron ore.

part sharply defined. The stratification in places is rendered very conspicuous for the reason that in the itabirite portions of the formation the iron-oxide layers are so frequently separated by thin partings of white quartz sand. These sandy partings, as planes of weakness, control to a considerable extent the weathering and fracturing of the beds. While the main bulk of the iron formation consists of sandy iron-oxide-bearing beds, there frequently occur, interbedded with these, shaly or schistose iron-oxide-bearing beds

showing that, while the mechanical sediments consisted mainly of quartz sand, clay also was frequently deposited in certain localities.

Thus it is clear that in structure and general occurrence the iron formation is so like ordinary sediments that there is little doubt as to its sedimentary origin. It remains, however, to account for its peculiar and unique composition and also for its enormous mass. It is difficult to picture a source for such an enormous amount of iron oxide as is contained in the iron formation, and even if an adequate source of supply be found, it is not so easy to see how the iron oxide came to be deposited locally in masses hundreds of meters in thickness with less than $\frac{1}{2}$ of 1 per cent of siliceous sediments intermixed.

It is apparent from the composition of the Caraça quartzite that during the first stages of the sedimentary deposition the processes of decomposition greatly exceeded in effectiveness the processes of mechanical disruption, for, instead of arkose sediments, the Caraça quartzite is made up of the products of mature weathering. This may be ascribed to a long period of decomposition without transportation, resulting in the accumulation of a thick mantle of residual material on the land surface, or it may be ascribed to a warm, moist climate, or to extensive wave action with practically continuous sedimentation. The material of which the sediments are composed was derived from the decomposition of rocks of the basement complex, such as granite, gneiss, amphibolite, and crystalline schists, with some basic intrusives. The principal minerals associated in the make-up of these rocks are quartz, feldspar, biotite, hornblende, and some pyroxene, whose end products after weathering are quartz, kaolin, hydrated iron oxide, and some aluminum hydroxide. These four constituents, therefore, probably made up the bulk of the decomposition products.

During the sedimentation which followed the post-Archean erosion period the first material to be deposited in central Minas Geraes was quartz sand, from which it is natural to suppose that the finer products of the decay of the basement complex—the kaolin and hydrated iron oxide—were carried farther out to sea, while the coarser quartz sand was deposited nearer the shore. This process must have been long continued, for the Caraça

quartzite is thick. Following the Caraça quartzite is the Batatal schist, the finer material of which implies a slackening in the vigor of sedimentation, whether because the land from which the sediments were being derived was becoming lower, or because the source of the sediment was becoming more remote owing to an advancing shore line, or because of deepening of waters or shifting of currents. The Batatal schist is thin, indicating that this stage was not long enduring. It was followed by local flows of basic lava. And then came the deposition of the iron formation. The hypotheses to explain this remarkable formation naturally are of two sorts: (1) that the iron oxide was a mechanical sediment washed in like the mud of the schist and the sand of the quartzite; (2) that it was precipitated from solution through either chemical or biochemical agencies.

Following the hypothesis that the iron oxide was a mechanical sediment, the source for the iron oxide should naturally be the residual material resulting from the thorough weathering of the rocks of the basement complex. Besides this hydrated iron oxide, the residual material should contain kaolin and quartz in somewhat greater proportion than the iron oxide. Under any hypothesis the sediments which resulted in the Caraça quartzite and the Batatal schist came from the sorting of thoroughly weathered material by stream and wave action. The Caraça quartzite represents a time when only material of the coarser sort, the sand grains, could find rest in the area under consideration. The finer material was swept farther out to sea to find lodgment in deeper and quieter waters. With the lessening of the vigor of the agents of sedimentation came the thin Batatal schist. At this time fine mud was being washed into the sea and deposited, while the coarser sand was either not washed into the sea or was left still nearer the shore which may have changed its position in the meantime. With the kaolin much iron oxide must also have been washed into the sea and not a little of it deposited with the mud.

Thus far the process has been the ordinary one of decay of igneous rocks and the deposition of much of the resulting material as clastic sediment. The unusual feature to be explained is what very peculiar condition obtained to cause the deposition of ferric

hydroxide pretty generally over the region and in some places the building up of a series of beds of ferric hydroxide in a high state of purity which sometimes totals several hundred meters in thickness. The completeness of the separation, as evidenced by the fact that much of the ore now contains 69 per cent iron out of a possible 70 per cent for chemically pure ferric oxide, and the vast extent of the iron formation are very hard to understand. The iron oxide resulting from the decomposition of granite, gneiss, amphibolite, and crystalline schists should be in a more or less finely divided condition, and as such should not be very generally separated from the sand and clay by any sorting action of running water or ocean waves, except in so far as affected by a higher specific gravity which might result in small local accumulations of iron sands, or in the association of smaller particles of iron oxide with larger particles of other materials in the sediments. The iron oxide should be with the schists and quartzites. Great masses of iron oxide containing less than $\frac{1}{2}$ of 1 per cent of impurity do not seem possible as the result of mechanical separation, though it is not impossible that a small percentage of the iron oxide in the iron formation may have been derived thus.

The alternative hypothesis is that the iron oxide was precipitated from solution following the formation of limestones as an analogy. This escapes the serious difficulties of separation of materials. As in the case of the limestones, to account for the purity it is only necessary to suppose that the deposition of the iron compound occurred in clear seas where comparatively little clastic sediment was being brought in. While the thickness of iron formation is great, it is exceeded by many limestones.

It is the nature of the precipitation that leaves the widest field for speculation. There are two possibilities: (1) the iron may have been precipitated directly from solution by purely chemical means, or (2) it may have been abstracted from the water by organisms and deposited as a sediment. In either case the iron may be supposed to have been in solution chiefly in the form of ferrous carbonate and to have been thrown down as ferric hydroxide.

There are various chemical reactions which can cause the precipitation of ferric hydroxide from solutions of ferrous carbonate,

of which in nature oxidation of the carbonate with the resulting hydrolysis is perhaps the most likely possibility. But such a reaction should necessitate a notable quantity of iron compound in solution. Van Hise and Leith object that river and sea-waters do not contain the requisite amount of iron.[1] Their suggestion that the iron in the various iron formations of the Lake Superior region has come from associated basaltic lavas, either from the magmatic waters or from chemical reactions between the hot basic lavas and the sea-water,[2] hardly seems applicable to the Brazilian iron formation, since nothing in the nature of basic lavas has been found within the sedimentary series of the iron-ore district with the exception of the serpentinized remains of one small flow near Cattas Altas. This is very insignificant in extent in comparison with the iron formation, and furthermore extensive lenses of iron formation occur higher up within the Piracicaba schist with which there are no igneous rocks associated. In chemical precipitation there is likewise to be considered the fact that chemical reactions would be likely to produce other precipitates in addition to ferric hydroxide, such as aluminum hydroxide and calcium compounds, which would result in the formation of impure deposits of iron ore rather than in thick beds and lenses of pure ferric hydroxide.

The other possibility is that the ferric hydroxide was thrown down by organic action. It is now known that much of the bog iron ore being formed in lagoons at the present time is the result of the activity of a certain group of bacteria known as the iron bacteria. The iron bacteria include many individual species, of which the thread bacteria *Chlamydothrix*, *Gallionella*, *Spirophyllum*, *Crenothrix*, and *Clonothrix*, and the coccus form *Siderocapsa* have perhaps been most carefully studied.[3] While the different species have individual morphological peculiarities of their own, the type

[1] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *Mon. 52*, *U.S. Geol. Surv.* (1911), pp. 503–6.

[2] *Op. cit.*, pp. 506–18.

[3] Hans Molisch, *Die Eisenbakterien*, p. 10, Jena, 1910; D. Ellis, "A Contribution to Our Knowledge of the Thread Bacteria," *Centralbl. für Bakt.*, Abt. II, Bd. 19 (1907), p. 502; Abt. II, Bd. 26 (1910), p. 321.

as a whole possesses certain general physiological characteristics. They all live in clear water, either standing or running water. Lieske states that he has never found any in turbid water, nor in waters containing a great deal of organic matter.[1] They live in waters containing iron compounds in solution which it is claimed by Winogradsky they utilize according to the following reaction: $2FeCO_3+O+3H_2O=2Fe(OH)_3+2CO_2$. Heat is liberated by this reaction, and this energy together with the carbon dioxide developed is utilized by the bacteria to sustain life.[2] Ferric hydroxide is left behind and may accumulate. Other investigators, like Molisch,[3] claim that ferrous compounds are not necessary for the physiological processes of these organisms and that organic compounds other than carbon dioxide must be present for their use. Nearly all agree, however, that their activity results in the accumulation of deposits of ferric hydroxide in many places. As the result of this activity the water pipes of cities where the water contains a considerable amount of ferrous carbonate have sometimes been completely closed.[4] That certain limonite deposits have been produced in this way is evidenced by the fact that in them large numbers of the sheaths of these bacteria have been found.[5] To quote from Lafar:

> The decomposing power of these organisms is very great, the amount of ferrous oxide oxidized by their cells being a high multiple of their own weight. This high chemical energy on the one hand, and the inexacting demands in the shape of food on the other, secure to these bacteria an important part in the economy of nature, the enormous deposits of ferruginous ocher and bog iron ore, and probably certain manganese ores as well, being the result of the activity of the iron bacteria.[6]

[1] Rudolf Lieske, "Beiträge zur Kenntnis der Physiologie von Spirophyllum ferrugineum (Ellis), einem typischen Eisenbakterium," *Jahrb. für wissenschaftliche Botanik*, XLIX (1911), 91–127.

[2] S. Winogradsky, "Über Eisenbakterien," *Botan. Zeitung*, Bd. 46 (1888), p. 261.

[3] Hans Molisch, *op. cit.*, p. 44.

[4] F. Lafar, *Technical Mycology*, I (1898), 361; also I (1910), 272.

[5] A. Fischer, *The Structure and Functions of Bacteria*, p. 69, tr. by A. Coppen Jones, Clarendon Press, Oxford, 1900.

[6] F. Lafar, cited by Van Hise and Leith, *op. cit.*, *Mon. 52*, *U.S. Geol. Surv.* (1911) p. 519.

Such a process as this would seem to offer a possible clue to the origin of the Itabira iron formation. As these bacteria thrive best in clear waters, the low proportion of clastic sediment in the formation is natural enough. If the deposition in general took place in lagoons and embayments and the thicker and more siliceous portions of the formation developed near the river mouths, in regions of currents, or other favorable localities, and the thinner, more uniform portions of the formation represent deposits formed

FIG. 17.—A view of the Peak of Conceição near Itabira de Matto Dentro, from the summit of Caué. The iron formation forms a continuous belt between Caué and Conceição.

farther off shore or in quiet waters near shore, the great and sudden variations in the thickness of the iron formation at various points may perhaps be accounted for. Much of the ferric hydroxide may have been formed as a flocculent precipitate in the sluggish river waters carrying little or no clastic sediment, and later deposited in a thick series of delta beds at the debouchures of the streams. Such may be the great accumulations of iron formation at Alegria, Gandarella, and elsewhere. Whatever the nature of this sedimenta-

tion, the field evidence appears to indicate that the deposition of the iron-oxide beds in these localities of unusual thickness took place with comparative rapidity.

While certain thin discontinuous layers of iron formation might be attributed to chemical percipitation, it is difficult to realize how great thicknesses over large areas could have been thus formed. Little is known concerning the concentration of iron compounds in solution necessary for chemical precipitation. It probably varies greatly with varying conditions, and the special conditions which would have to be assumed as causing the deposition of the Brazilian iron formation must have extended over large, as well as widely scattered, areas since this formation is not only found throughout a considerable area in Minas Geraes but also exists in the extreme western part of Brazil, nearly a thousand miles to the west. On the other hand, there is experimental evidence that bacteria do precipitate iron oxide out of very dilute solutions, and it is only necessary to assume the presence of large numbers of these micro-organisms in scattered localities to account for the presence of the iron formation. Unfortunately the metamorphism which the iron formation has suffered makes it impossible to recognize organic remains, if such were originally present. Recognizable bacterial remains, however, are stated to be extremely short-lived and it is difficult to identify them even in modern bog-iron-ore deposits. There is also to be considered the fact that nowhere in the ocean do we know of extensive deposits of ferric hydroxide being formed at the present time. This objection, however, is equally valid in case of ferric hydroxide precipitated either chemically or biochemically, and therefore must be considered under either hypothesis. In the formation of bog ores on continental areas bacteria are known to play an important part, but chemical precipitation is probably effective also, and it is difficult to say which plays the principal rôle. In spite of various uncertain factors, however, the deposition by micro-organisms seems more easily to explain the various unusual phases of the Brazilian iron-formation sedimentation, and we prefer to adopt this hypothesis, at the same time, however, realizing fully the inadequacy of our present knowledge concerning bacteria as a

geological agency, and the necessity for further investigation on this most important subject.

MANGANESE ORES

With the exception of gold, manganese ore is the most important of the metalliferous mineral products of Brazil at the present time. Two mines in central Minas Geraes, the Morro da Mina mine north of Lafayette, and the Wigg mine east of Miguel Burnier, are in continuous operation, while several smaller mines produce ore intermittently. Among these are the Rodeio mine near Kilometer 508, east of Miguel Burnier on the Ouro Preto branch of the Central Railroad of Brazil, the Cocuruto mine southwest of Lafayette, and the Queluz das Minas mine near the Morro da Mina mine north of Lafayette. Many abandoned and inactive mines occur in the general vicinity of the mines mentioned above.

The manganese deposits of central Minas Geraes may be separated into two distinct classes: (1) those occurring in the basement complex and (2) those occurring in the overlying sediments. The deposits found in the region around Lafayette belong to the first class, while those occurring along the Ouro Preto branch railway east of Miguel Burnier are of the second class. The centers of these two districts, having distinct types of deposits, are not more than 25 kilometers apart, and some of the mines in the one can be seen from the other. The deposits have been described in detail by Derby[1] and by Scott,[2] so that only a general outline need be given here in order to show their relation to the general stratigraphy.

The manganese deposits which are found in the basement complex consist of large irregular masses of manganese oxide inclosed in, or bounded by, gneiss, granite, or crystalline schist. Individual masses such as that at Morro da Mina may be more than a hundred meters in their longer diameter. While irregular in shape, they are usually somewhat elongated, suggesting lenses. They occur

[1] O. A. Derby, "On the Manganese Ore Deposits of the Queluz (Lafayette) District, Minas Geraes," *Am. Jour. Sci.*, XII (1901), 18–32; "On the Original Type of Manganese Ore Deposits of the Queluz District, Brazil," *ibid.*, XXV (1908), 213–16.

[2] H. K. Scott, "The Manganese Ores of Brazil," *Jour. Iron and Steel Inst.* (1900), p. 179.

scattered through the basement complex without any apparent regularity, but most of them appear to have either gneiss or crystalline schist on one or both bounding walls.

The manganese oxide composing these lenses is usually in the amorphous form, occurring mainly as psilomelane and wad, though pyrolusite also is found with these. According to detailed studies made by Dr. Derby,[1] it appears that these oxides are surface decomposition products of other manganese minerals which have in one or two cases been encountered below the zone of oxidation. Of these minerals the principal ones are the manganese silicates, tephroite and spessartite, and with these occur rhodochrosite, the manganese carbonate, and sparingly rhodonite, another manganese silicate. These minerals occur intimately intermixed in varying proportions, one being more abundant in one place and another elsewhere, and together they form a reddish manganese silicate and carbonate rock. The relation of the manganese rock to the inclosing crystalline rocks has not been definitely determined; it may be interlayered with the gneiss or crystalline schist or perhaps it is intrusive into them.

From the one or two instances noted it is judged that all the manganese oxide deposits in the areas of basement complex are surface oxidation products of such masses of manganese silicate and carbonate rock. In many of the deposits where the original rock has not been encountered, the oxide ores have textures which are duplicated in the manganese silicate and carbonate rock elsewhere, and therefore suggest a similar origin. During the process of decomposition more or less solution and redeposition takes place, with the result that certain portions of a deposit are composed of high-grade manganese oxide, while other portions contain admixtures of other products of decomposition, such as clay and quartz sand. Most of the ore is hard, but soft material, mainly wad and pyrolusite, also occurs abundantly, being irregularly intermixed with it.

Manganese ores associated with igneous rocks, such as those described above, occur abundantly in India and are also found locally in the eastern United States.

[1] O. A. Derby, *Am. Jour. Sci.*, XXV (1908), 215–16.

The manganese deposits in the sedimentary series occur as definite beds associated with the iron formation. The principal bed, that on which the Wigg mine is situated, is 3 or 4 kilometers in length, and at its maximum reaches a thickness of over 2 meters. It strikes in an east-west direction parallel to the strike of the inclosing sediments and corresponds with them in dip, making it apparent that the manganese ore bed was laid down as a sedimentary bed just as the inclosing rock. The bed at the Wigg mine is bounded on one side by soft itabirite, with a contact zone of mixed soft hematite and manganese oxide, and on the other side by a ferruginous schist associated with the iron formation.

The manganese bed at the Rodeio mine is of smaller horizontal extent but of greater thickness than that at the Wigg mine and shows less definitely its relation to the inclosing rocks. In the case of both of these deposits, beds of carbonate rocks consisting of a mixture of calcium, magnesium, iron, and manganese carbonates are found in the vicinity. These, however, occur at different horizons from the manganese beds.

The manganese ores associated with the sedimentary rocks consist of finely crystalline or amorphous manganese oxides, probably largely a mixture of pyrolusite and psilomelane. From their occurrence it must be assumed that they are similar in origin to the associated rocks, that is, that they are original sedimentary deposits of manganese oxide which have been somewhat altered and recrystallized by subsequent metamorphism. The source of the manganese is doubtful, but it may very well have been derived from deposits of manganese ore in the basement complex such as now occur to the south near Lafayette. Decomposition of such deposits may have yielded a large amount of residual manganese oxide which was worked over, transported, and deposited as beds or lenses in the sedimentary series. Their origin would thus be very similar to that of the iron ores of central Minas Geraes with which they are closely associated.

Sedimentary manganese ore beds similar to those of central Minas Geraes are found in many places on other continents, probably the best known of them being those in northern Arkansas, those in central Chile, those in the Caucasus near the Russian boundary, and those in western Arabia.

GOLD

Gold was known to occur in Brazil even in the early days of its settlement and it was the search for this metal which brought many of the explorers and settlers to the new country. However, not until the beginning of the eighteenth century was the great gold field of Brazil, that occurring in central Minas Geraes, actively worked. It was at this time that the towns of Sabara, Marianna, and Ouro Preto, the latter then known as Villa Rica, were founded

FIG. 18.—Ouro Preto, former capital of Minas Geraes. A city built by the gold-mining industry. The hills on all sides show the results of placer mining.

in rapid succession. A period of great excitement and activity followed, which continued in waves as districts were extended and new ones discovered, almost to the middle of the nineteenth century. From that time on the industry rapidly decreased in importance until 1889 when gold mining as a general industry practically ceased as a result of the abolition of slavery. At the present time there are only two important gold mines operated in Minas Geraes. These are the Morro Velho mine at Villa Nova de Lima near Bello Horizonte and the Passagem mine at Passagem near Ouro Preto.

Nearly all the early workings were shallow open cuts or shafts, or short tunnels. Later development led to the operation of a few deep mines, such as the Descoberto mine near Sabara, the Gongo Socco and São Bento mines between Caethé and Santa Barbara, the Pary mine near São Francisco, and the Santa Anna and Maquiné mines near Marianna. The shallow workings cover large areas and are widely distributed in central Minas, groups of them being found in the vicinity of nearly all the small towns and villages, for in most cases it was the gold mines that caused the founding of the villages. Some of the areas of old abandoned workings cover many hundreds of acres.

Gold occurs in Minas Geraes in three different associations: (1) in quartz or sulphide veins, (2) disseminated in the iron formation and in the canga derived from it, and (3) in stream gravels.

Gold-bearing quartz veins occur with different relations; some of them are strike veins, others occur along bedding or schistosity planes; some are long and continuous, others short and lens-like. In some places groups of short parallel or intersecting veins are found, while elsewhere single isolated veins of considerable extent occur.

Quartz or sulphide veins containing gold may occur in the basement complex or in any of the sedimentary formations. The Morro Velho mine at Villa Nova de Lima is operating a large vein in the Piracicaba schist on which they have descended for a vertical distance of more than 1,700 meters, deeper than any other gold mine in the world. The Passagem mine near Ouro Preto is working on an irregular bedding vein impregnating a thin layer of Batatal schist between the Caraça quartzite and the Itabira iron formation. In the old workings near Ouro Preto quartz veins are found cutting the Caraça quartzite and the Itabira iron formation. Near Cattas Altas old workings are found in the basement complex and here also quartz veins occur. Many other examples might be given of quartz veins found in the various formations.

The mineral veins of the district for the most part come under two general heads: (1) ordinary quartz veins, and (2) veins of magmatic origin. To the first class belong certain quartz-hematite veins occurring in the iron formation, and the numerous barren

quartz veins found throughout the district, while to the second class belong the quartz-feldspar pegmatites and the gold-bearing quartz, or quartz-sulphide veins.

The quartz-hematite veins in the iron formation consist of quartz in which flakes of specular hematite occur. The hematite may be found in large, irregular, curved flakes along cracks, or it may be imbedded within the solid quartz. These and various barren quartz veins are of little or no importance as gold-bearing veins. They are probably ordinary circulating water depositions, as the quartz does not contain inclusions of monazite, zircon, rutile, garnet, or xenotime, some of which are nearly always present in the quartz in pegmatite veins and in igneous rocks.[1] It is possible, however, that this evidence may not be conclusive and that by more detailed study some of these veins may be found to be hot-water depositions.

The quartz-feldspar pegmatite veins have already been mentioned in the description of the rocks of the basement complex. They consist of quartz, feldspar, and muscovite with which other minerals, such as beryl, columbite, tourmaline, etc., are sometimes associated in minor quantities. They occur only in rocks of the basement complex and are not gold-bearing.

The gold-bearing quartz and sulphide veins are the important sources of gold in the district. They occur in various formations and differ somewhat in mineral composition in different localities. In some places free gold occurs in quartz, sulphides being inconspicuous, while elsewhere the gold occurs in arsenopyrite, pyrrhotite, or pyrite associated with a variable amount of quartz. Other minerals occurring in places in or near these veins are calcite, cyanite, biotite, garnet, oligoclase, tourmaline, albite, siderite, muscovite, and others.

At the Passagem mine[2] the principal sulphide minerals are arsenopyrite, pyrrhotite, and pyrite, occurring in a gangue of quartz, or quartz and decomposed oligoclase, strongly impregnated with tourmaline. The oligoclase is altered to calcite and white mica. With these occur in varying abundance the other minerals

[1] Specimens examined by Dr. Derby.

[2] A. J. Bensusan, "The Passagem Mine and Works," *Inst. Min. and Met.*, Twentieth Session, October 19, 1910.

mentioned above. Dr. Derby[1] has made a study of the genesis of the mineral and ore deposition at this mine and has established three successive stages of mineralization. He believes that the original quartz-oligoclase deposition was of a pegmatitic nature, the material being derived from some intrusive igneous mass which, however, has not yet been discovered. For although nowhere in the district has any evidence been found of igneous intrusions into the sedimentary series, the nature of the mineralization is such as to leave no doubt as to its magmatic origin. During the deposition of the quartz and oligoclase it appears that garnet (andradite), biotite, cyanite and staurolite were developed locally along the contact, these minerals occurring in the country rock along the border of the vein. Crystals of apatite are associated sparingly with the garnet. Graphite also is associated with the contact minerals, being found along shearing planes.

The second stage of mineralization, according to Dr. Derby, consisted in the introduction of tourmaline along cracks and as impregnations into the earlier minerals.[2] This stage was very pronounced, tourmaline being one of the principal gangue minerals. Its introduction was closely followed by the third stage, namely the sulphide mineralization, by which were introduced arsenopyrite, pyrrhotite, and pyrite. During the introduction of both the tourmaline and sulphides, the alteration of the oligoclase to calcite and white mica took place. Both tourmaline and sulphides occur with the white mica and calcite in the decomposed oligoclase masses, their abundance depending on the degree of alteration. There is evidence that the tourmaline and sulphide solutions attacked the contact minerals as well as the vein material. The biotite is decomposed in places, and tourmaline and sulphides are commonly associated with the contact minerals.

In the vicinity of the gold-bearing lode, but not directly connected with it, are certain geodes with the following mineral association: calcite, siderite, albite, quartz and muscovite. The

[1] O. A. Derby, "On the Mineralization of the Gold Bearing Lode of Passagem, Minas Geraes, Brazil," *Am. Jour. Sci.*, XXXII (1911), 185–90.

[2] *Op. cit.*, p. 190.

origin of these and their relation to the minerals of the gold-bearing lode has not yet been determined.

Summarizing the foregoing statements we may separate the various minerals into the following groups:

Original Vein Minerals	Contact Minerals	Later Vein Minerals		Geode Minerals
Quartz	Garnet	Tourmaline	Arsenopyrite	Calcite
Oligoclase	Biotite		Pyrrhotite	(surface etched)
(largely altered	(locally		Pyrite	Siderite
to white mica	altered)	Secondary Minerals		(surface dissolved)
and calcite)	Staurolite			Albite
	Cyanite	Sericite		Quartz
	Apatite	Calcite		Muscovite
	Graphite			(with sericite)
	(associated			
	with contact			
	minerals)			

The famous Morro Velho mine at Villa Nova de Lima, which has been the greatest gold-producer in Minas Geraes, is operating on a vein in the Piracicaba schist. This vein is parallel to the bedding which here dips toward the southeast at an angle of about 45°. It has an average width of 5 to 10 meters, and this notable width continues with some variation to the greatest depth yet reached, which in 1912 was more than 1,600 meters below the surface. The lode reaches a length of more than 150 meters along the strike.

While the country rock is the Piracicaba schist, the gangue material is a fine-textured mixture of carbonates (siderite, dolomite, and calcite) with quartz, and, according to Dr. Derby, a small amount of albite.[1] The ore consists principally of pyrrhotite with smaller amounts of arsenopyrite, pyrite, and chalcopyrite. A notable feature of the vein is its constancy in width, mineralization, and values through the numerous levels down to the lowest one yet opened.[2]

[1] O. A. Derby, "Notes on Brazilian Gold Ores," *Trans. Am. Inst. Mining Eng.*, XXXIII (1902), p. 282–87.

[2] For a brief history and general statistics of these mines see: H. K. Scott, "The Gold-field of the State of Minas Geraes, Brazil," *Trans. Am. Inst. Min. Eng.*, XXXIII (1902), 406–44.

The gold disseminated through the iron formation and resulting canga formed the basis for most of the gold-mining operations in the early years. A considerable proportion of the iron formation being soft, it was washed almost as easily as stream gravels and, therefore, was attractive to the early miners.

Gold occurs as the native element disseminated in the Itabira iron formation, as well as in the iron-formation lenses of the Piracicaba schist. It may be found in hard, or soft ore, or in itabirite, but generally it occurs in the soft schistose phase of the iron formation known as "jacutinga" (see p. 389).[1] Most of the old workings are in soft itabirite, or in soft, powdery ore, doubtless because of the facility of operating in these formations. The gold is very unequally disseminated within the iron-formation belts, there being large areas of iron formation in which little or no gold occurs, and other places where it is found gathered in rich pockets. There is no regularity in the distribution of the gold-bearing portions of the iron formation and no apparent physical condition, unless it be difference in porosity, which would cause the localization in the places where it occurs. Because of the irregularity of distribution and the disseminated nature of the gold, this type of deposits has never formed the basis of large individual operations. The deposits were worked during the time of slavery because of the cheapness of labor, but when slavery was abolished the workings were abandoned.

The gold occurring in the iron formation is of varying coarseness, from fine dust, hardly visible to the naked eye, to fragments several centimeters in length. Even large masses are reported to have been found. The larger pieces have a porous, spongy texture and contain intermixed particles of iron oxide and quartz. The particles of gold are generally elongated or platy in form, owing to deposition along the lamination planes of the iron formation.

Most of the gold occurring in the iron formation is very pure and contains but very little alloyed silver or other metals. Locally, however, there are occurrences of what is known as *ouro branco* (white gold), which consists of an alloy of gold and palladium.

[1] E. Hussak, "O Palladio e a Platina no Brazil," *Annaes da Escola de Minas de Ouro Preto*, N. 8 (1906), p. 96, tr. by Miguel A. R. Lisboa, and Manoel A. R. Lisboa.

This alloy has been encountered in a number of places, but is nowhere very abundant.

Quartz in veins or lenses is very common in the iron formation, and in places contains gold. It is very often found where disseminated gold occurs, and it is possible that some genetic relation exists between the gold in the quartz and that disseminated in the iron formation. As the masses of vein quartz in this association are generally small, irregular, and discontinuous, it seems possible that, because of the porous nature of the formation, the gold-bearing waters did not follow regular channels but impregnated the iron formation for considerable distances on both sides of the main lines of flow and thus deposited their gold in a more or less disseminated condition. At any rate, from its form and occurrence it is certain that the gold is a secondary concentration within the iron formation.

Gold occurs in the gravels of most streams rising in, or flowing through, the gold-bearing district (Fig. 19). These occurrences are simply placer deposits whose gold has been derived in part from gold-bearing quartz veins, but mainly from the great masses of iron formation, the disseminated gold of which, because of its widespread occurrence, offers abundant opportunity for concentration along streams.

At present small gold-washing operations are conducted by natives along many of the streams at the end of each rainy season, since the flood waters caused by the heavy tropical rains bring new material down the valleys each year.

DIAMONDS

The principal diamond fields of Brazil are those of central Minas Geraes near Diamantina, of Western Minas Geraes near Bagagem, and of Bahia near the towns of Sincora, Lencoẽs, and Jacobina. Of these the Diamantina field is the oldest and best known and has yielded most of the best Brazilian diamonds. The Bagagem field has yielded most of the large diamonds found in Brazil, while the Bahia field supplies nearly all the world's demand for carbonados.

The Diamantina field is located in the Serra do Espinhaço quartzite belt, the principal workings lying north, east, and south

of the town of Diamantina. They occur on portions of the main tableland which forms the watershed between the Rio Jequitinhonha and the Rio São Francisco, as well as on highlands between the upper tributaries of the Rio Jequitinhonha.

The Serro do Espinhaço in this portion of its extent is a belt of uneven, rolling tableland from which rise numerous small, irregular quartzite knobs and ridges. The plateau is deeply cut into by the

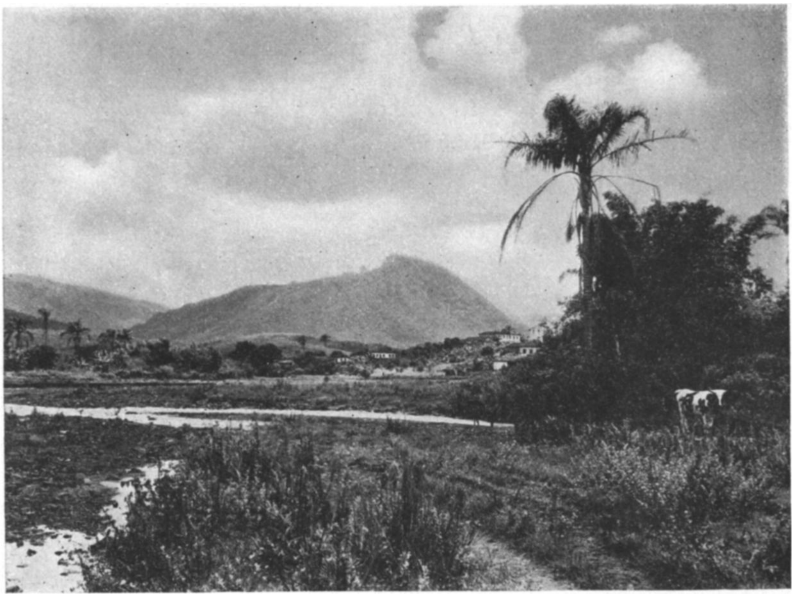

FIG. 19.—The Rio Gualaxo at Antonio Pereira. The scene of much placer mining in the past and where small gold-washing operations are still conducted by natives at the end of each rainy season. The prominent peak is that of Frazão, a lens of hard quartzite in the Piracicaba schist.

headwaters of the Jequitinhonha which form great, rocky gorges. The gorges are, however, comparatively recent, and by far the larger portion of the region still remains as broad stretches of uplands known in Brazil as *chapadas*. Above the general level of the uplands in the eastern part of the district rises an old monadnock, the isolated peak of Itambé, which is one of the highest points in Minas Geraes. The uplands have a general elevation varying from

1,200 meters to 1,300 meters above sea-level. The Jequitinhonha where it leaves the district has an elevation of about 900 meters, while Itambé rises above the uplands to an elevation of 2,000 meters above the sea; thus the greatest relief in the district is about 1,100 meters.

The tablelands or *chapadas* are of great interest, both geologically and commercially, for it was on them that the diamonds were

FIG. 20.—The diamond-washing of Serrinho near Curralinho. In the distance is the monadnock of Itambé.

first concentrated and it is on them that the principal deposits are now found. The *chapadas* are, for the most part, underlain by Caraça quartzite, dipping uniformly but generally at low angles to the east. On many of them, especially those near the actual watershed of the Serra do Espinhaço, there are remnants of what were once more extensive deposits of gravel, sand, and clay. These have been called the Diamantina conglomerate. The remnants lie on the eroded surface of the Caraça quartzite, and when examined carefully it is found that most of them occur in irregular trough-like depressions, the bottom and walls of which consist

of quartzite (Fig. 21). Many of these troughs reach a depth of 30 meters or more, though some of the deeper ones scarcely exceed 100 meters in width (Fig. 22). No determination has been made of their maximum width, while as to their original longitudinal extent nothing is known. From their irregular occurrence and their relation to the underlying quartzite it is presumed that these deposits are for the most part the result of stream deposition.

FIG. 21.—The pit of Serrinho. A shallow depression in the Caraça quartzite which was partially filled with diamond-bearing conglomerate. The conglomerate and beautifully white kaolin are seen in the bottom of the excavation. The final washing operations to recover the diamonds are conducted in the *batêa*, or jig, under the thatched roof.

This view is further strengthened by the nature of the materials composing them and the relation of the different kinds of material to each other. By detailed mapping it might be possible to connect all these remnants so as to reproduce the old drainage network as it was when the conglomerate was deposited.

The gravel, sand, and clay occur associated in the deposits as beds, lenses, or masses, without any regularity. Locally beds of pure

clay, or clay slightly intermixed with sand, occur, while elsewhere abundant pebbles are scattered through clay or sand matrices. The nature of the pebbles in different parts of the district varies, but the characteristic and dominant pebbles consist of quartzite, undoubtedly derived from the Caraça formation. Associated with these are pebbles of iron formation, quartz, schist, diorite, amphibolite, and other rocks, the association varying in different

FIG. 22.—The trench at Cadette's mine, northwest of São João da Chapada

localities. A characteristic but less abundant pebble in these deposits is the diamond.

Where exposed at the surface the conglomerate is very hard and indurated, but beneath the surface both matrix and pebbles, especially those of quartzite, are in many places soft and friable. This softening of the quartzite pebbles bears evidence of considerable age of the conglomerate deposits.

In many respects these deposits are strikingly similar to certain deposits of gravel, sand, and clay which occur along the Appalachian region in the United States. In Georgia these contain bauxite;

farther north in scattered localities they contain concentration deposits of brown iron ore and manganese ore. In the United States these deposits have been referred to the Tertiary or late Cretaceous.

From the great predominance of quartzite pebbles it must be supposed that the materials composing these soft conglomerate deposits came largely from the Caraça quartzite. The immediate source of the igneous pebbles present in some localities, however, is less certain. These may once have been laid down in conglomerate beds in the Caraça quartzite and have been worked over again later, or they may have been derived from the rocks of the igneous area adjacent to the Espinhaço sedimentary belt. The Caraça formation in this district is a well-consolidated quartzite of medium-grained uniform texture. Conglomerate beds are rare, and though scattered pebbles are frequent, these are almost invariably of vein quartz. There is a possibility, however, that pebbles of igneous rock may be present locally.

Accepting the supposition that the material composing the conglomerate was derived largely from the Caraça quartzite, one would naturally look for the origin of the diamonds in the same formation. In the Diamantina district, diamonds have never to our knowledge been found in the Caraça quartzite. It is, however, possible that they may occur so widely scattered that it is only by repeated concentration such as has occurred in the conglomerate deposits that they become noticeable. In the Grão Mogul district of northern Minas Geraes about 200 kilometers to the northeast of Diamantina, diamonds are reported to be found in hard quartzite[1] from which they are freed by blasting. However, it is not known whether this is the Caraça quartzite or whether it belongs to some other formation.

In conformity with the generally accepted theory of their origin, the diamonds may have been derived originally from intrusions of igneous rock at a distance from the present areas of concentration. Disintegration and decomposition of the inclosing rocks would have resulted in the freeing of the diamonds, leaving them

[1] O. A. Derby, "Modes of Occurrence of the Diamond in Brazil," *Am. Jour. Sci.*, 3d Ser., XXIV, 39.

in residual accumulations subject to removal by streams and other subaerial agencies. If in part transported to the sea during the deposition of the Caraça formation, they should be found probably in association with quartz sand and such pebbles of vein quartz as resisted the abrasian of stream action. Being the hardest of all minerals and the most resistant to decomposition, it is not surprising that the diamonds still retain their crystalline faces when most other minerals originally present, except quartz, have disappeared.

When in pre-Devonian times the sedimentary series was elevated, consolidated, and metamorphosed, and the processes of erosion had commenced, the diamonds began gradually one by one to be freed from the quartzite and collected in the stream deposits along with other minerals from the same source. This continued for long ages, and while other minerals were disintegrating and decomposing, the diamonds remained intact and became more and more concentrated. Even after a general peneplain level was reached, this process probably continued and was only interrupted by renewed elevation resulting in the present gorges.

The foregoing discussion is based on the hypothesis that the diamonds at one stage in their history were incorporated in the Caraça quartzite. The alternative hypothesis is that the majority of them never have been deposited in the quartzite, but that they were brought in by streams directly from igneous areas some distance from the present diamond fields. An objection to this hypothesis is that so few igneous pebbles occur in the conglomerate, and that over large areas pebbles of igneous rocks are entirely absent. However, it is possible that, on account of their predisposition to rapid decay, they might have disappeared in the slow, shifting process on the peneplain surface. But one wonders why, if such diamond-bearing igneous-rock areas exist, not concealed by the sedimentary rocks, they have not been discovered up to the present time. If the diamonds were brought in from a long distance the *chapada* diamond-bearing gravels should necessarily occur along a few main drainage courses and not be irregularly scattered over a wide area, while if they came from igneous areas close by, the diamonds should have been discovered in streams flowing from these areas. But in the present state of knowledge it

seems best to leave the question whether the diamonds in these *chapada* conglomerate deposits have, for the most part, been derived directly from igneous rocks of the Archean complex, or whether, coming in any case from that source originally, there occurred an intermediate stage of incorporation in the Caraça quartzite—an open one.

Perhaps the most noted of the diamond mines of this district is that of São João da Chapada, which has been rather fully described by Dr. Derby.[1] It is located some 30 kilometers northwest of Diamantina on the tableland which represents the old base-leveled surface. Sunk in the solid quartzite of the tableland is a steep-walled trench, perhaps 500 meters long and now about 30 meters in depth (Fig. 23). This trench has the appearance of being the channel of an old stream which became completely filled with residual clay, sand, and gravel when the surrounding region was close to the base level. This alluvial-filled trench has been cleaned out again as the deposits of clay, sand, and gravel have been washed away in the process of diamond mining.

Dr. Derby in several of his papers has been inclined to the hypothesis that the diamonds of São João da Chapada are vein minerals,[2] derived from a pegmatite vein of which there seems to be some evidence in the cut. Certain masses of pure-white kaolin containing nests of large and beautiful crystals of quartz, which have never been exposed to the wear of running water, look much like the decay products of a pegmatite vein. Unfortunately at the time of our visit in 1912 the mine had not been worked for twenty years, so that definite and reliable information was not easily obtained, but from the accounts given by some of the people at São João da Chapada and the published papers which touch upon this point, it would seem that the diamonds were far more abundant and characteristic of the waterworn conglomerates, especially where pebbles of higher specific gravity (iron ore, itabirite, etc.) were

[1] O. A. Derby, "Brazilian Evidence on the Genesis of the Diamond," *Jour. Geol.* VI (1898), 121–46; "On the Association of Argillaceous Rocks with Quartz Veins in the Region of Diamantina, Brazil," *Am. Jour. Sci.*, 4th Ser., VII 343–56.

[2] O. A. Derby, "Modes of Occurrence of the Diamond in Brazil," *Am. Jour. Sci.* 3d Ser., XXIV, 34–42; "The Genesis of the Diamond," *Science*, IX (1887), 57–58.

common, than of those particular clayey portions which suggest a pegmatitic source. Because of this the São João da Chapada occurrence does not seem essentially different from the other diamond-bearing conglomerate deposits. A pegmatitic dike, being less resistant than the surrounding quartzite, may have determined the location of the drainage channel in the first place, and because of its ready yielding gave rise to the steep-sided trench which would

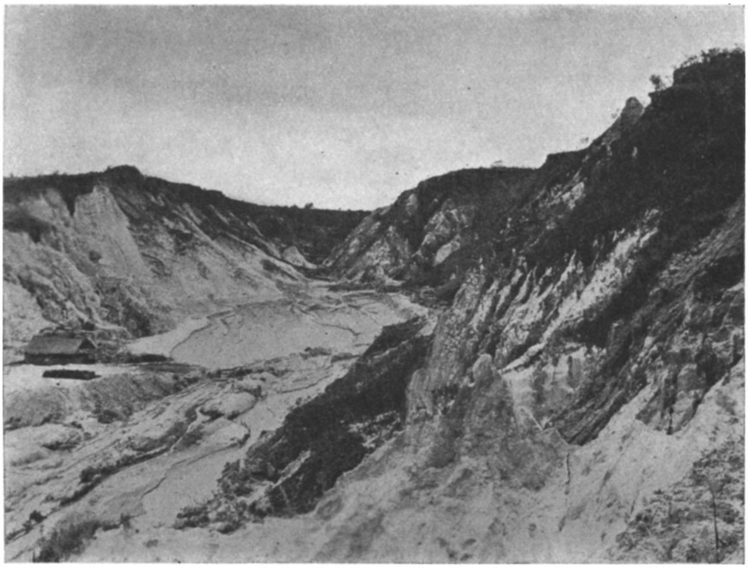

FIG. 23.—The famous diamond mine of São João da Chapada. The conglomerate-filled trench in the quartzite has now been largely re-excavated, the undisturbed quartzite appearing at various points in both walls and in the bottom of the excavation. This mine has produced some of the finest of the Brazilian diamonds.

otherwise seem peculiar in a peneplained surface. But we believe that if such pegmatitic material was present it was only a contributing condition, and that the diamonds came with the material that was washed into the trench filling it up.

Since their deposition with the residual base-level gravels which now constitute the *chapada* or upland deposits, several reconcentrations of the diamonds have occurred, as the region has suffered various changes of attitude. Upon the rejuvenation of the drainage

the streams began dissecting the old nearly base-leveled plain, first cutting through the surface decomposition products and associated fluviatile deposits, and then attacking the underlying quartzite. As the *chapada* deposits were being removed in this erosive process, the softer and lighter materials were being worn finer and washed away, while the heavier diamonds remained behind and became further concentrated in the stream gravels of the immediate

FIG. 24.—Diamond mining at Cadette's mine. The clay and materials of lesser specific gravity are washed away by running water while the diamonds and other heavy pebbles remain behind and become concentrated.

vicinity. At several stages during this erosion there were periods when the downward cutting of the streams was checked and they began to widen their valley bottoms and deposit material over them. Then active cutting began again, leaving gravel-covered terraces on the valley slopes. Much material from these several gravel terraces as well as from the diamondiferous conglomerate of high-level *chapadas* has since been washed down the present steep

valley slope into the Jequitinhonha River. This has resulted in the following distribution of the diamond-bearing deposits. Numerous remnants of *chapada* deposits still occur upon the plateau in areas as yet undissected by the rejuvenated streams. Gravel deposits of later age occur lower down on valley terraces at various elevations above the present stream beds. Gravel and sand deposits of still more recent age occur along the present stream

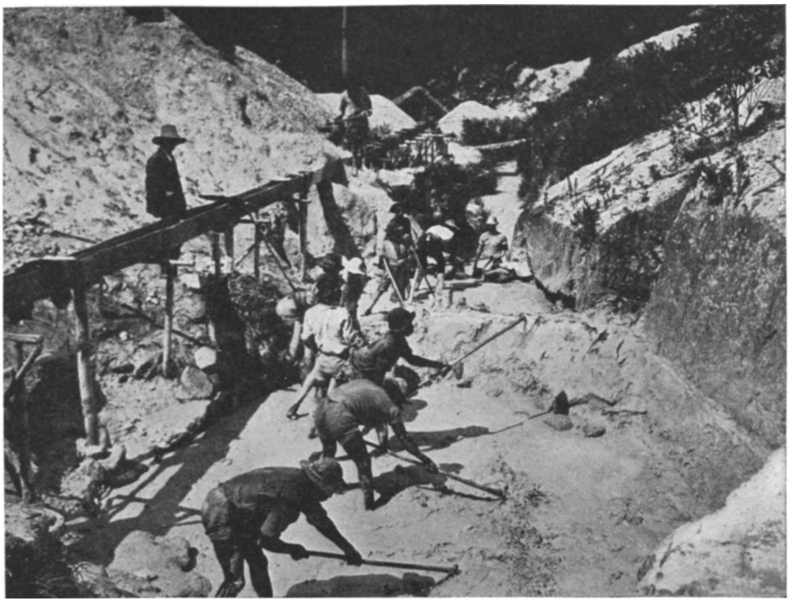

FIG. 25.—Stirring up the mortar-like mass of diamond-bearing clay and gravel

bottoms. All these deposits contain diamonds in greater or less abundance.

The present-day practice for the recovery of the diamonds is simply a furtherance of the process of concentration which has been going on in nature. When a considerable quantity of soft kaolin and loose gravel from the diamondiferous conglomeratic deposits has been accumulated in the bottom of the trench, or mine, a stream of water is conducted through the trench (Fig. 24). As the running water passes over this loose material, natives armed with a sort of

hoe keep the mass constantly stirred up, so that it has a general consistency and appearance not unlike thin mortar (Fig. 25). The running water carries away the clay and materials of lesser specific gravity, while the coarse portions of the gravel, and the minerals of higher specific gravity such as the diamond, fragments of hematite, etc., remain behind. Later, after screening out the coarser pebbles, the diamonds are picked out of the final concentrate on the *batêa*, or washing sieve, by hand.

The diamonds of the Diamantina district generally show dodecahedral crystallization with rounded faces. Many of those in the *chapada* deposits have rough faces and a dark grayish-green coating, but the majority have smooth or striated faces. Some of the stones in the present river gravels show surface corrasion.

The majority of the diamonds mined in the district vary in size from $\frac{1}{4}$ carat to 4 or 5 carats, though occasionally stones are found weighing up to 10 carats. The largest diamonds ever found in the Diamantina district, according to Dr. Derby,[1] weighed less than 100 carats, and very few have been found weighing over 50 carats. The largest of the Brazilian diamonds—the "Star of the South," the "Star of Minas," and the "Dresden" diamonds—have all come from the Bagagem district in southwestern Minas Geraes.

In brilliancy the Diamantina diamonds exceed the South African diamonds, and there is a smaller percentage of "off-colored" stones found. Beautiful bluish-white stones are abundant, and stones of other colors such as lemon-yellow, cognac-brown, rose, green, and blue are occasionally found.

We are indebted to Professor T. C. Chamberlin, Professor C. K. Leith, and Professor Eliot Blackwelder for criticisms and suggestions, and to Dr. O. A. Derby for much information.

[1] O. A. Derby, "A Notable Brazilian Diamond," *Am. Jour. Sci.*, XXXII (1911), 191.